US010737799B2

(12) **United States Patent**
Hedrick

(10) **Patent No.: US 10,737,799 B2**
(45) **Date of Patent: *Aug. 11, 2020**

(54) **PRECISION OPERATOR FOR AN AIRCRAFT AUTOTHROTTLE OR AUTOPILOT SYSTEM WITH ENGINE PERFORMANCE ADJUST**

(71) Applicant: **Geoffrey S. M. Hedrick**, Malvern, PA (US)

(72) Inventor: **Geoffrey S. M. Hedrick**, Malvern, PA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **16/159,348**

(22) Filed: **Oct. 12, 2018**

(65) **Prior Publication Data**

US 2019/0047715 A1 Feb. 14, 2019

Related U.S. Application Data

(63) Continuation-in-part of application No. 15/900,542, filed on Feb. 20, 2018, and a continuation-in-part of (Continued)

(51) **Int. Cl.**
B64C 13/00 (2006.01)
B64D 31/10 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***B64D 31/10*** (2013.01); ***B64D 43/00*** (2013.01); ***F02C 7/26*** (2013.01); ***F02C 9/26*** (2013.01); ***F02C 9/54*** (2013.01); ***G05D 1/0072*** (2013.01); ***G05D 1/0816*** (2013.01); ***G05D 3/12*** (2013.01); ***G08G 5/0008*** (2013.01); ***G08G 5/04*** (2013.01); *F05D 2220/323* (2013.01);
(Continued)

(58) **Field of Classification Search**
None
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,363,480 A 1/1968 Murphy
4,513,235 A 4/1985 Acklam
(Continued)

FOREIGN PATENT DOCUMENTS

DE 197 12 153 10/1998
EP 0137610 4/1985
(Continued)

OTHER PUBLICATIONS

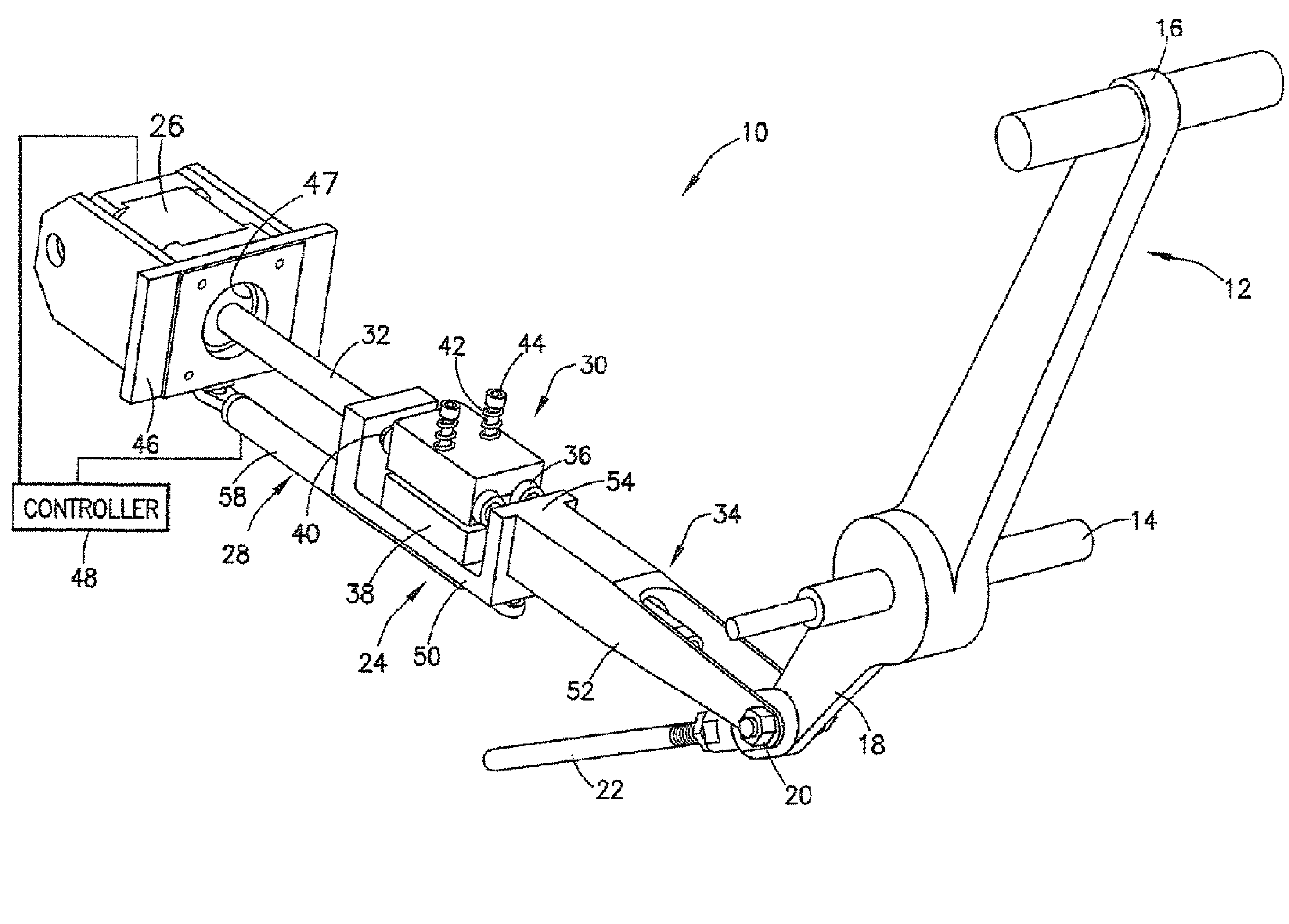
Office Action dated Mar. 19, 2019 issued in European Patent Application No. 16862626.5.
(Continued)

Primary Examiner — Adam M Alharbi
(74) *Attorney, Agent, or Firm* — Cozen O'Connor

(57) **ABSTRACT**

An autothrottle system for an aircraft includes a motor, actuator assembly, and position sensor operatively connected between the motor and a moving portion of the actuator assembly. An electronic controller is configured to control the motor to move the actuator assembly to actuator positions based at least on position information from the position sensor to move the throttle lever to lever positions.

10 Claims, 7 Drawing Sheets



Related U.S. Application Data

application No. 15/554,642, filed on Aug. 30, 2017, now Pat. No. 10,099,795, said application No. 15/900,542 is a continuation-in-part of application No. PCT/US2016/045002, filed on Aug. 1, 2016.

(60) Provisional application No. 62/336,200, filed on May 13, 2016, provisional application No. 62/250,819, filed on Nov. 4, 2015.

(51) **Int. Cl.**

F02C 9/54	(2006.01)
F02C 7/26	(2006.01)
G08G 5/00	(2006.01)
G08G 5/04	(2006.01)
G05D 1/08	(2006.01)
G05D 1/00	(2006.01)
G05D 3/12	(2006.01)
B64D 43/00	(2006.01)
F02C 9/26	(2006.01)

(52) **U.S. Cl.**

CPC .. *F05D 2270/051* (2013.01); *F05D 2270/093* (2013.01); *F05D 2270/12* (2013.01); *F05D 2270/13* (2013.01); *F05D 2270/20* (2013.01); *F05D 2270/303* (2013.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,516,063	A	5/1985	Kaye	
4,567,786	A	2/1986	Sakurai	
5,152,360	A	10/1992	Haefner et al.	
5,188,316	A	2/1993	Dressler et al.	
6,028,280	A	2/2000	Winkler	
6,973,915	B1	12/2005	Henle	
8,855,890	B2	10/2014	Egle	
2002/0131864	A1*	9/2002	Vos	B60W 10/06 416/25
2005/0150206	A1	7/2005	Verniau	
2007/0235594	A1	10/2007	Wingett et al.	
2011/0112705	A1	5/2011	Antraygue	
2016/0086396	A1*	3/2016	Nutaro	G07C 5/0808 701/29.4
2017/0096236	A1*	4/2017	Nelson	B64D 45/00

FOREIGN PATENT DOCUMENTS

EP	0265738	5/1988
EP	2826707	1/2015

OTHER PUBLICATIONS

Roh'lix® Linear Actuators BINSDOCID: XP 55492757A Mar. 26, 2017 4 pages.

Search Report dated Jul. 24, 2018 which issued in the corresponding European Patent Application No. 16862626.5.

* cited by examiner

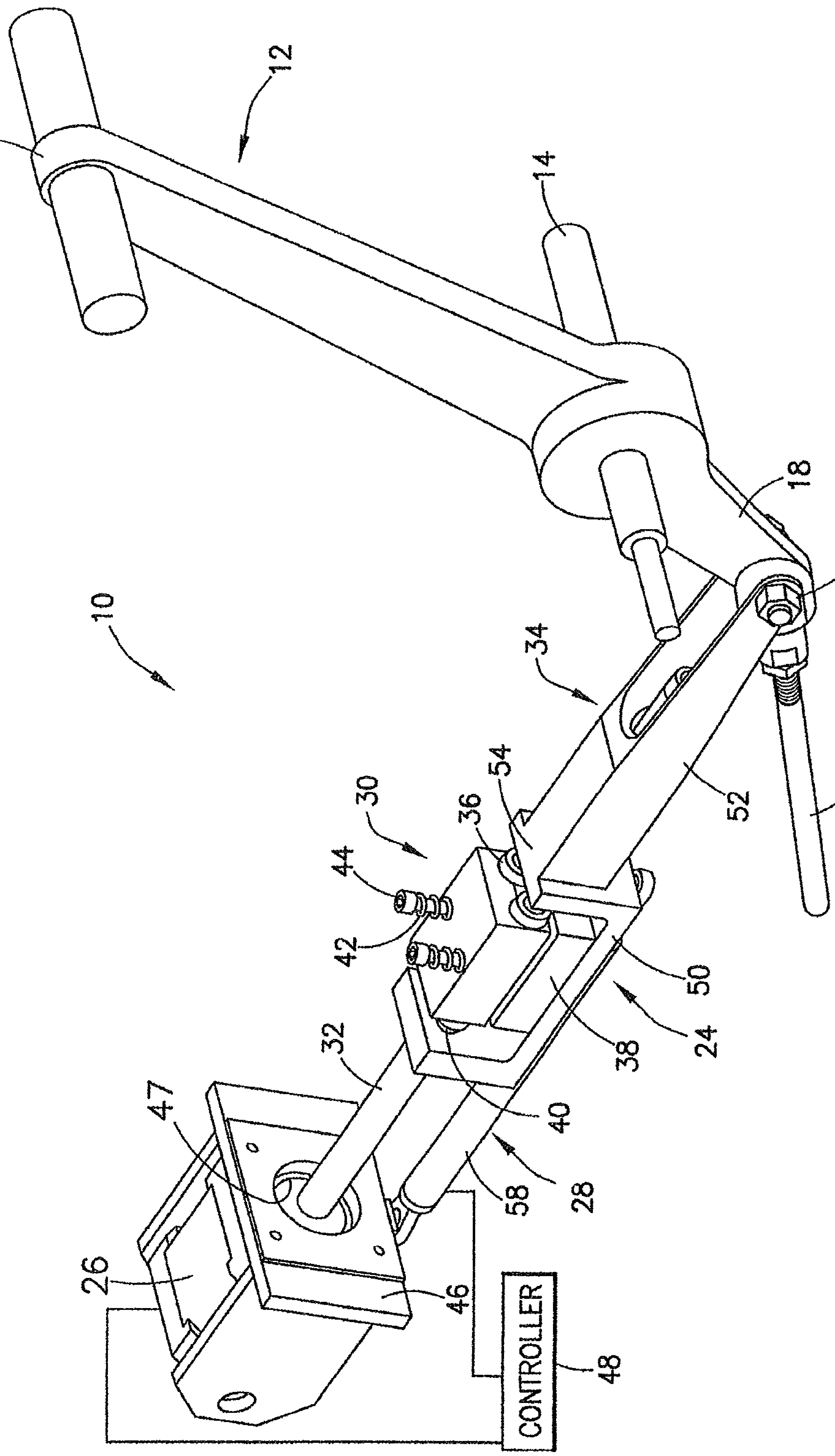
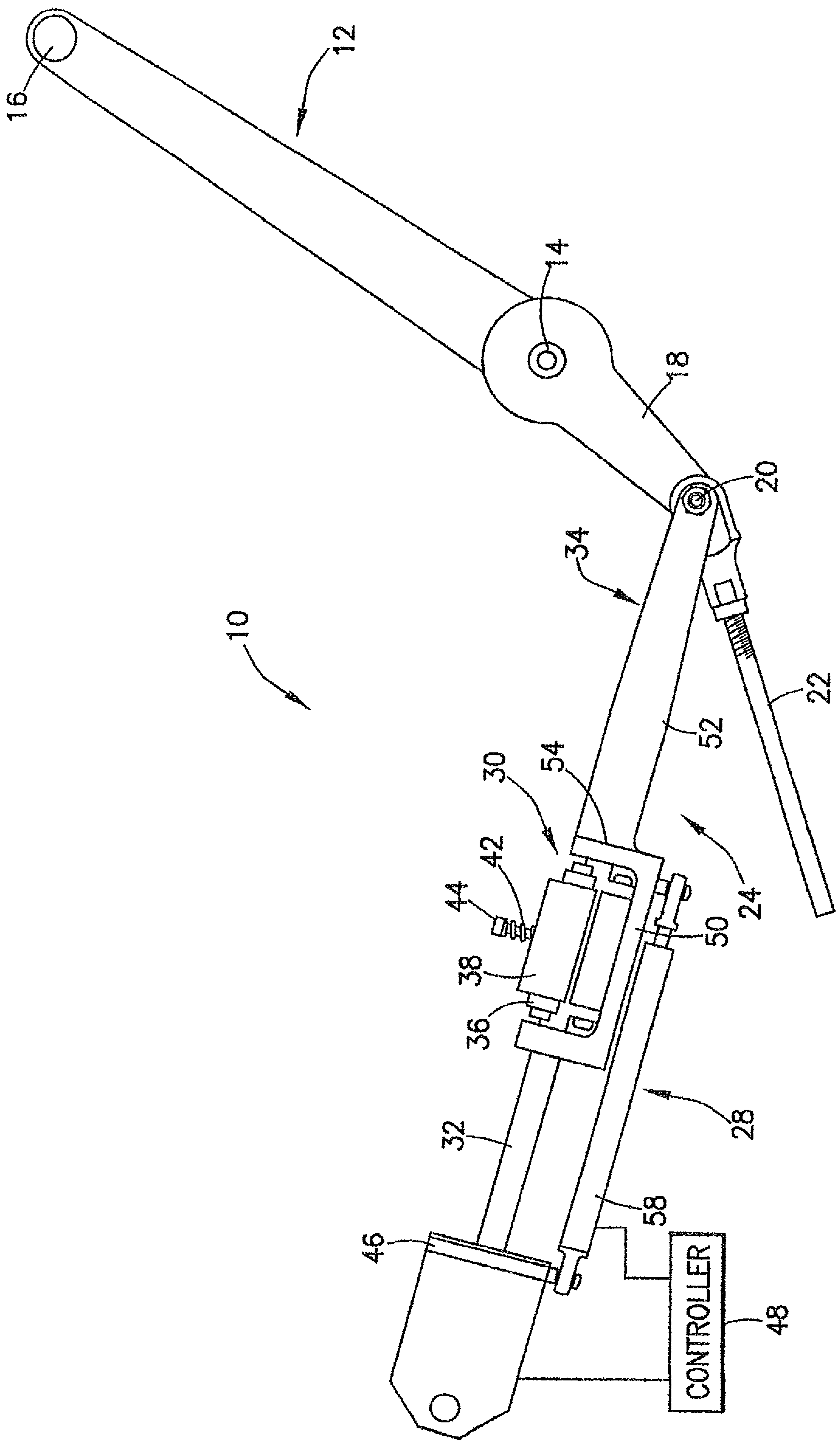

12
16
14
18
20
10
34
54
30
36
44
42
22
52
50
24
38
32
40
47
28
58
26
46
CONTROLLER
48

FIG. 1



12
16
14
18
20
34
10
22
52
54
30
24
42
44
50
38
36
28
32
58
46
CONTROLLER
48

FIG.2

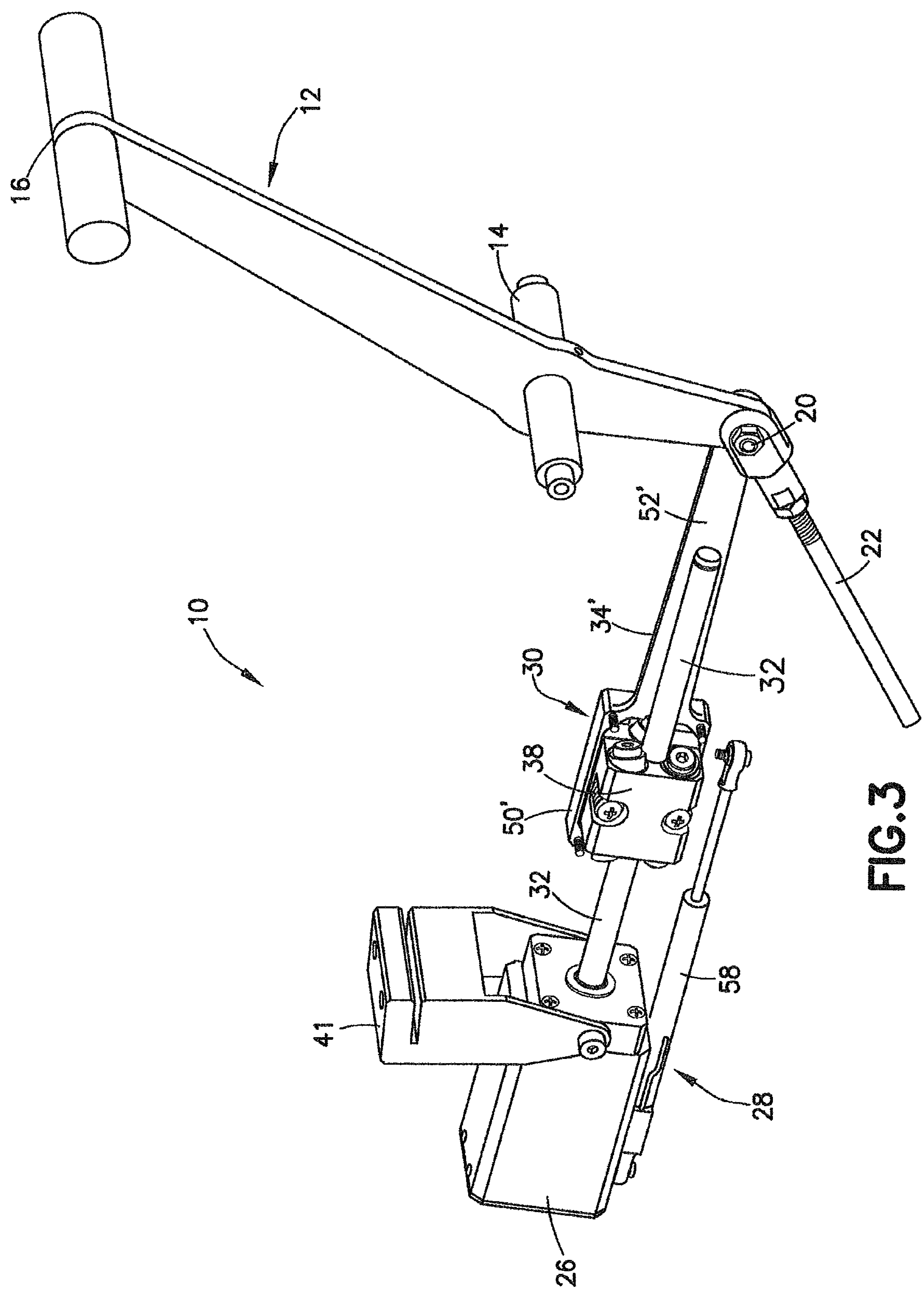


FIG.3

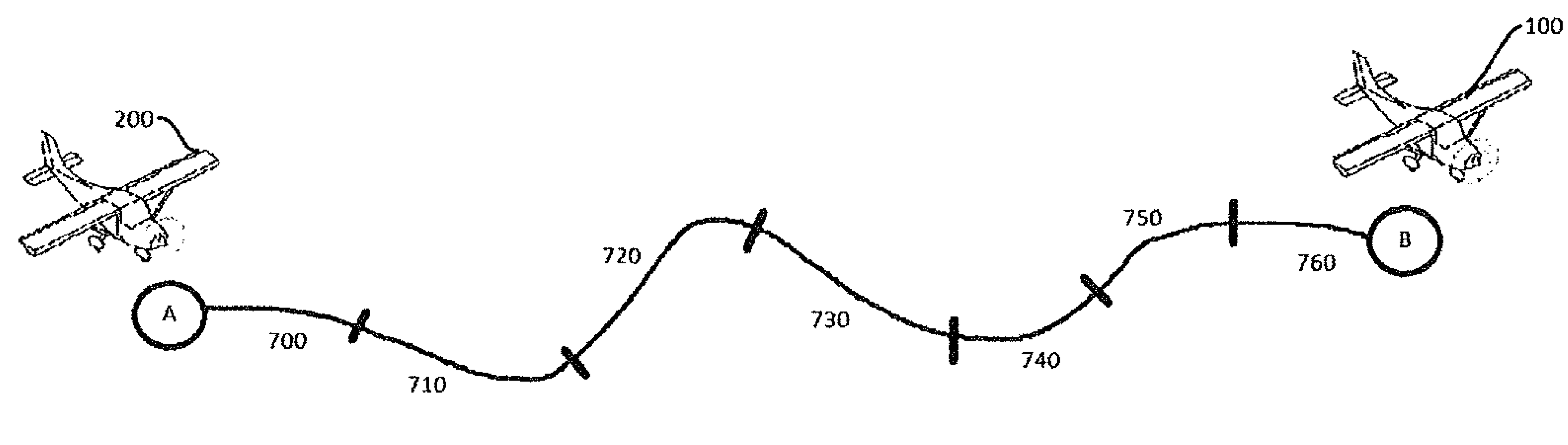

200
100
A
B
700
710
720
730
740
750
760

Fig. 7

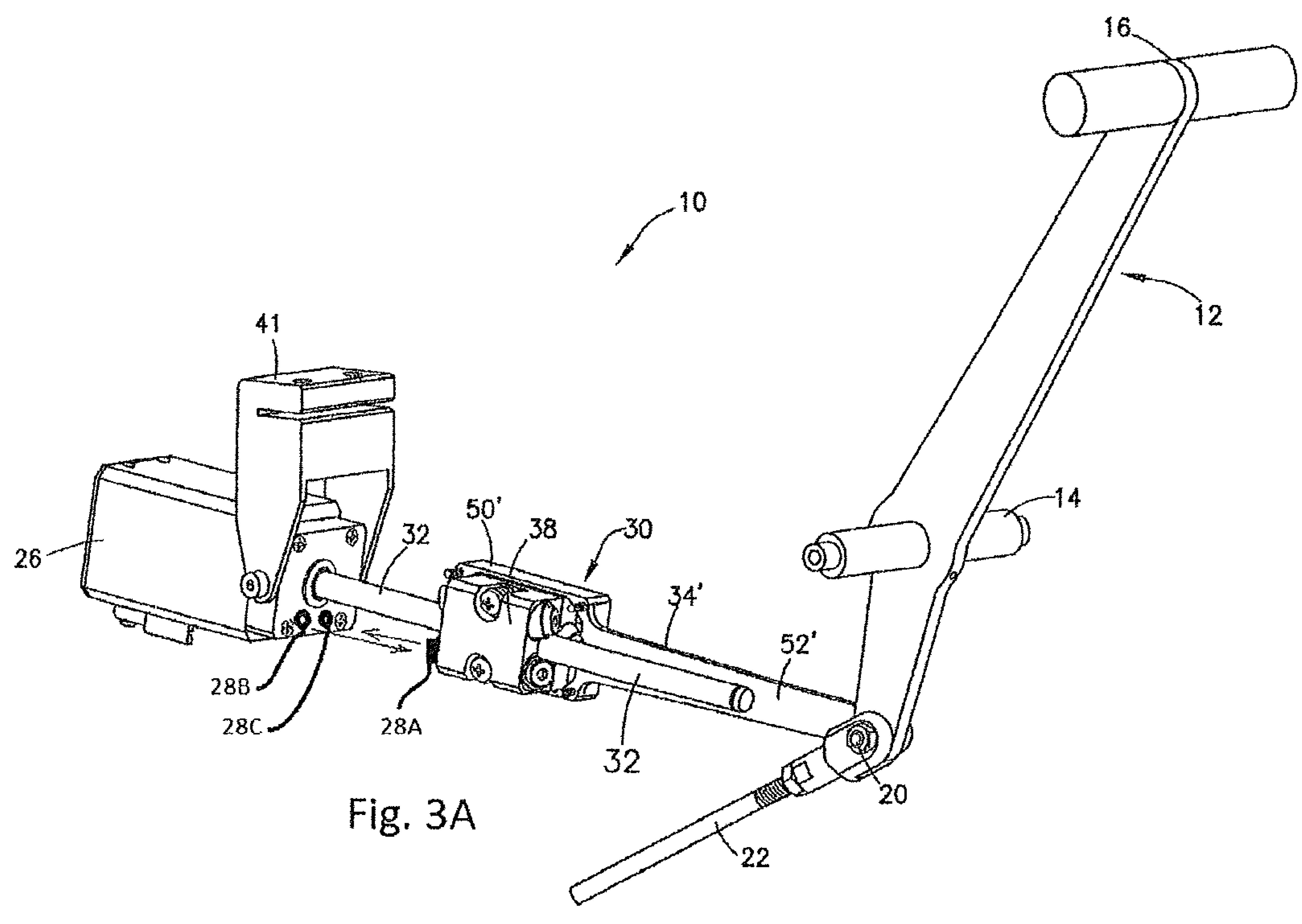

16
10
12
41
14
26
32
50'
38
30
34'
52'
28B
28C
28A
32
20
22

Fig. 3A

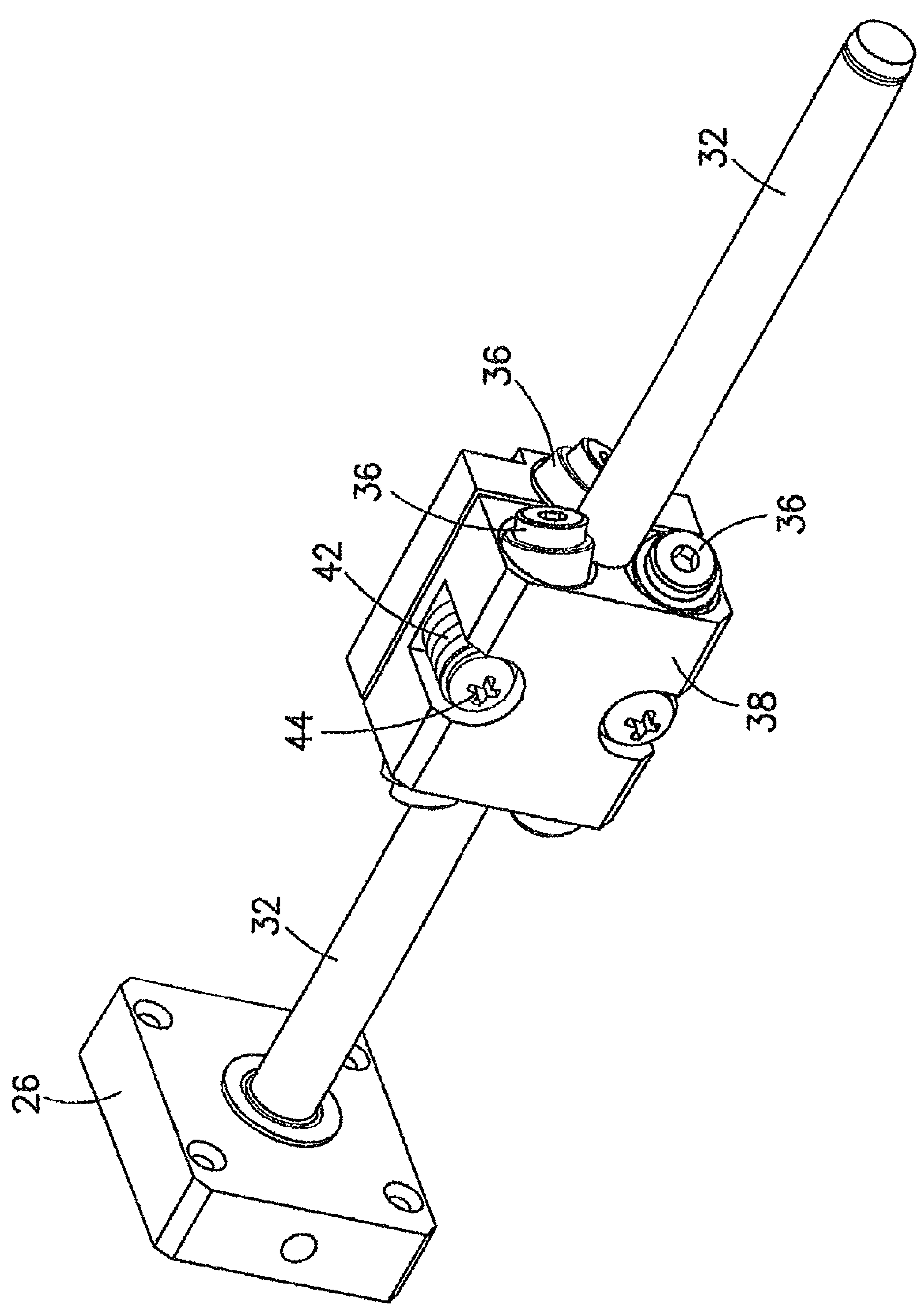


FIG.4

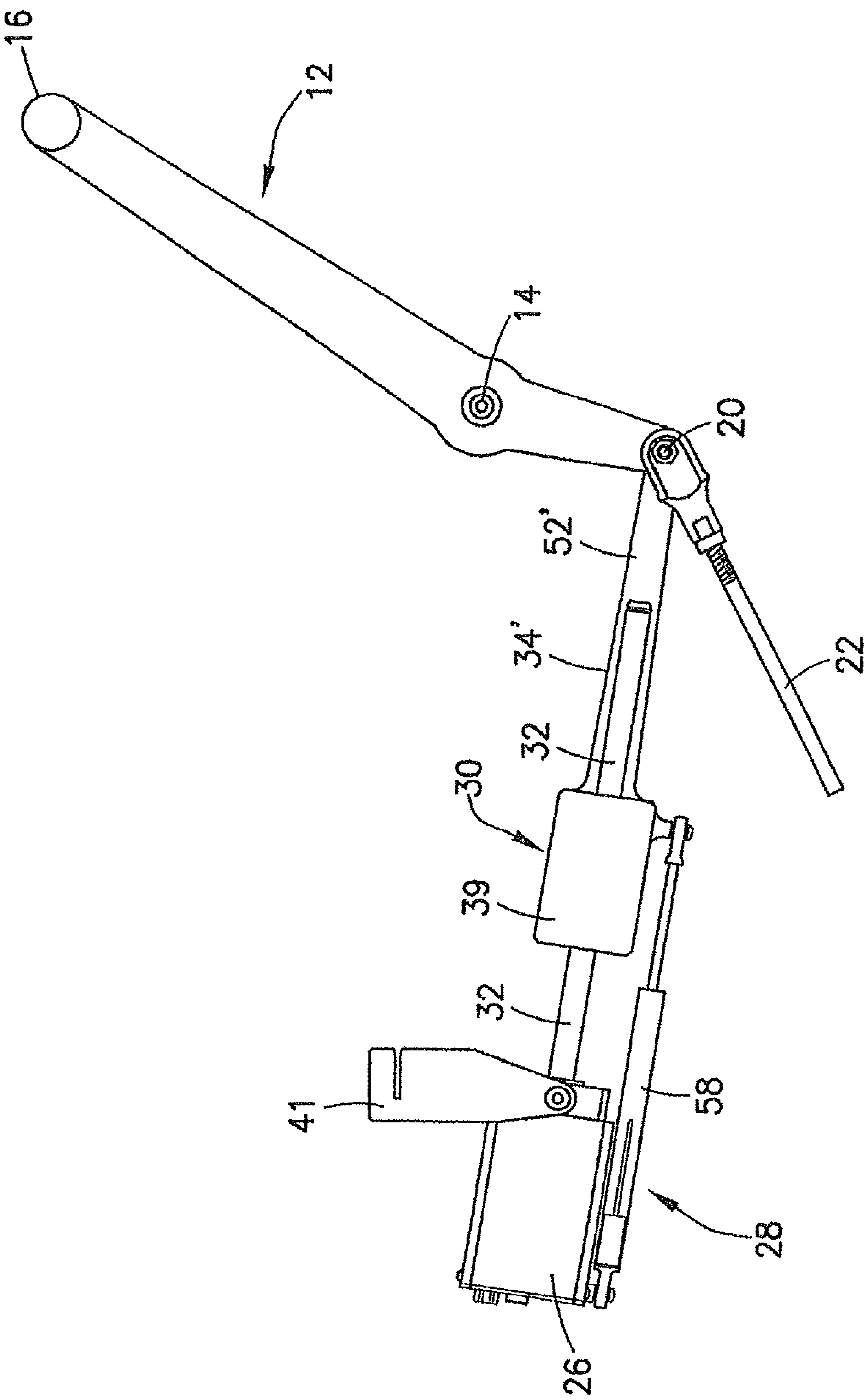
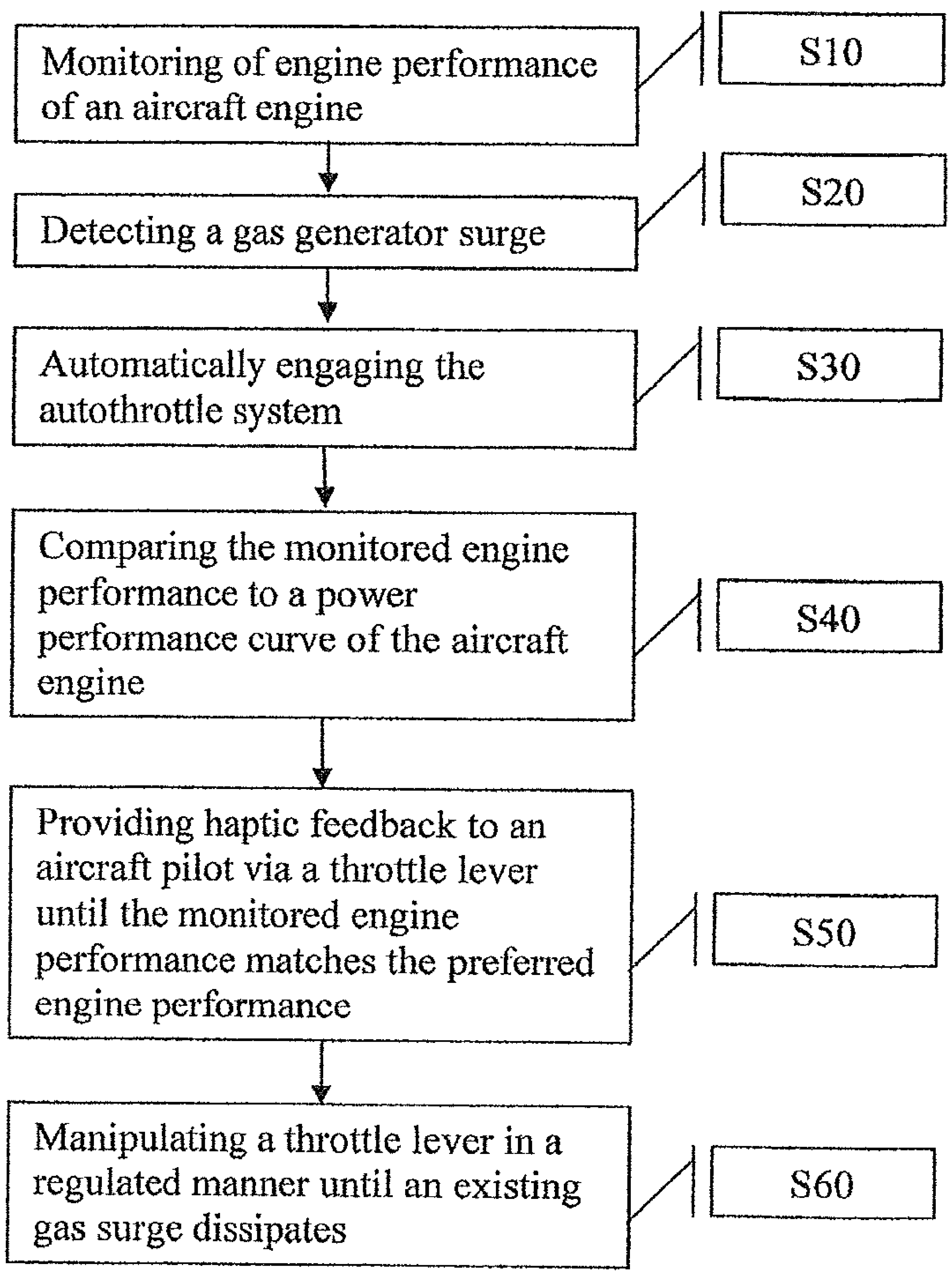


FIG.5

Fig. 6


Monitoring of engine performance of an aircraft engine
S10
Detecting a gas generator surge
S20
Automatically engaging the autothrottle system
S30
Comparing the monitored engine performance to a power performance curve of the aircraft engine
S40
Providing haptic feedback to an aircraft pilot via a throttle lever until the monitored engine performance matches the preferred engine performance
S50
Manipulating a throttle lever in a regulated manner until an existing gas surge dissipates
S60

PRECISION OPERATOR FOR AN AIRCRAFT AUTOTHROTTLE OR AUTOPILOT SYSTEM WITH ENGINE PERFORMANCE ADJUST

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of U.S. patent application Ser. No. 15/900,542, entitled "Precision Operator for an Aircraft autothrottle or Autopilot System With Engine Performance Adjust" filed Feb. 20, 2018, and U.S. patent application Ser. No. 15/554,642, entitled "Precision Operator for an Aircraft autothrottle or Autopilot System With Engine Performance Adjust" filed Aug. 30, 2017, which is a national phase of PCT Application No. PCT/US2016/045002, entitled "Precision Operator for an Aircraft autothrottle or Autopilot System," filed Aug. 1, 2016, and claims priority to U.S. Provisional Patent Application No. 62/336,200, entitled "Precision Operator for an Aircraft autothrottle or Autopilot System," filed May 13, 2016, and U.S. Provisional Patent Application No. 62/250,819, entitled "Precision Operator for an Aircraft autothrottle or Autopilot System," filed Nov. 4, 2015; all of which are incorporated herein by reference in their entirety.

FIELD THE INVENTION

The disclosed embodiments relate to an aircraft autopilot system. In particular, the disclosed embodiments relate to a precision operator for an aircraft autopilot system, and more specifically to an arrangement by which selective control for automated mechanical adjustment of aircraft throttle controls and/or aircraft flight control surfaces can be effected while accommodating ready manual override of the automated operator when deemed necessary or otherwise at the behest of the pilot or other operator of the aircraft. Specifically, the autothrottle will handle a rapid decrease or increase of power in a regulated manner despite a vehicle operator's attempt to override the autothrottle in certain situations, such as a go round.

BACKGROUND OF THE INVENTION

Aircraft flight decks have become increasingly sophisticated and rely to a large extent on technology and automated controls that have significantly reduced pilot workload and enhanced systems reliability and efficiency and, as such, passenger safety. In addition to advanced navigation capabilities provided by, for example, GPS and graphical displays that contribute to greatly improve situational and operational status awareness, advances in autopilot systems have proven of tremendous assistance to pilots in maintaining both aircraft control and the smooth and efficient operation of those aircraft that are provided with such capabilities.

Autopilot systems provide functions that range from, at the lowest end of the range of capabilities, simple wing leveling to, in more advanced systems, aircraft directional and course control to maintain and track a selected course, altitude maintenance and adjustment control, and adjustments to the aircraft throttle(s) to maintain and effect desired changes in aircraft velocity.

Automated control of the aircraft throttle(s), in particular, presents special problems that have, in the past, limited such capabilities to only the largest or, at least, the most technologically complex and advanced aircraft, such as large commercial airline passenger jets, advanced regional and general aviation jets, and high-end turbine propeller airplanes. Such autothrottles provide the ability to realize truly automated, hands-off control of the aircraft, thus providing increased aircraft operating efficiencies, reducing cost in, for example, the consumption of fuel, and vastly decreasing pilot workload and thereby notably increasing flight safety. But providing autothrottle capabilities in an aircraft requires, with the technologies currently in use, physical, spatial and mechanical accommodations that limit this functionality to only the largest and/or most technologically advanced aircraft which, in most cases, must be designed and constructed to include and utilize autothrottle functionality.

In most aircraft, the throttle(s)—which are selectively adjustable to cause the engine(s) to generate a predetermined amount of power or thrust to propel the aircraft at a desired velocity—are adjusted by pilot-controlled manual override displacement of one or more graspable handles on levers that are pivotally mounted for rotation through a limited arc in a throttle quadrant in the aircraft cockpit or flight control deck. These levers are typically connected to the engines or engine controllers by control cables that are longitudinally displaced as the positions of the throttle levers are pivotally adjusted.

In almost any aircraft, not insignificant forces must be applied to the throttle levers—whether manually by a pilot or by an operating motor of an autothrottle system—to vary or adjust the pivoted positions of the levers. The motors of the system, therefore, must be fairly robust, both in size and weight (to provide sufficient torque and operating forces applied to the throttle lever) and in construction (to assure continued reliability through tens of thousands of activations and operations). As a consequence, only aircraft specifically designed and constructed with sufficient clearances and space to accommodate these motors and associated elements at, in and/or alongside the throttles quadrant of the cockpit, and capable of accepting the significant additional weight associated with these systems and their component parts, are able to incorporate such autothrottles into and with their flight controls. There is moreover virtually no ability to retrofit or add autothrottle capabilities into existing aircraft that have not already been specially designed and constructed to accommodate the associated operating components of an autothrottle system.

It is in addition important, to assure safe operation of the aircraft under continued control by the pilot, that the pilot can quickly and easily override or otherwise assume manual control of the throttles from an activated autothrottle system in the event that operating conditions in the aircraft may suddenly require that the pilot assume immediate physical control of the throttles, as in an emergency or any circumstance in which the pilot deems it appropriate, without having to first manually disengage the autopilot or autothrottle system(s). Such circumstances, however may have a detrimental result in that sudden pilot engagement may cause operations of the aircraft throttle control outside of a desired throttle range. Such an occurrence can lead to slow engine responses or even a stalling condition at a worst case scenario. Accordingly, an improved autothrottle is beneficial to deter or prevent pilot operation of an autothrottle outside of a desired operating range.

SUMMARY OF THE INVENTION

The disclosed embodiments are directed to an aircraft autopilot/autothrottle operator arrangement that is compact, lightweight, reliable and readily installable in an aircraft, even in aircraft in which no special accommodation for adding or providing autopilot/autothrottle capabilities have been designed into or provided for the aircraft, and which can be safely and easily overridden by a pilot wishing to quickly assume manual control of the throttle(s) when under the control of the autopilot/autothrottle system. The disclosed embodiments provide such an operator arrangement that can also be applied, with like advantageous functionality, as part of or in conjunction with an aircraft autopilot system to control the movements of control surfaces of the aircraft whose variable positions are adjustable to control, for example, the pitch, roll and yaw of the aircraft. Additionally, the autothrottle can be used anywhere that an engine has to be controlled. For example, the autothrottle can be adapted to control a drone, an engine driving an oil rig, and the like.

The disclosed embodiments provides an aircraft autopilot/autothrottle operator that exhibits a number of significant advantages over those currently in widespread use. First, the inventive arrangement is relatively lightweight, especially as compared to current autopilot/autothrottle operating arrangements and components. Second, the inventive arrangement is notably simplified, as compared to current autopilot/autothrottle operating arrangements, which can provide significant increases in physical and operating reliability. Third, the inventive arrangement is notably more compact than current autopilot/autothrottle operating arrangements and is therefore installable in a wider range of aircraft of widely varying size. Fourth, the inventive arrangement is based on the use of a linear operator that is activated from a position remote from the throttle handle pivot, thus allowing its installation—either at the time of initial construction or as an add-on or retrofit to an existing structure—in aircraft having a relatively compact throttle quadrant or that have not otherwise been specially designed to accommodate a conventional autopilot/autothrottle and its heavy-duty motors and clutches and which would otherwise be mounted at and proximate the pivot points of the throttle handles. Fifth, the actuator utilized in the inventive arrangement does not require separate or integrated clutches or clutch components and instead provides inherent override capabilities, and neither does it require a series of gears between an operating motor and its attachment to the throttle handle—thereby greatly decreasing complexity, weight and physical space requirements and increasing operating reliability.

In one aspect, the disclosed embodiments provide an autopilot system including a motor configured to impart rotational movement to a shaft extending from the motor, the motor being mounted on a support. An actuator assembly is operatively connected to the shaft and to an attachment end of a throttle lever, the throttle lever having a control end, opposite to the attachment end, for application of manual force. A position sensor is operatively connected between the motor and a moving portion of the actuator assembly. The system further includes an electronic controller configured to control the motor so that it moves the actuator assembly to actuator positions based at least in part on position information received from the position sensor to cause movement of the throttle lever to lever positions. The actuator assembly includes a bearing assembly having a plurality of bearings configured to contact a surface of the shaft for converting rotational movement of the shaft into linear motion of the bearing assembly along the shaft. The actuator assembly further includes a shuttle arm having a mounting surface at a first end configured to attach to the bearing assembly and at least one linkage arm at a second end of the shuttle arm which is operatively coupled to the attachment end of the lever.

The disclosed embodiments may include one or more of the following features. The actuator assembly may be configured so that manual movement of the control end of the throttle lever applies a thrust force to the distal end of the shaft relative to the bearing assembly; and when the thrust force exceeds a threshold, the bearing assembly is configured to slip along the shaft irrespective of any rotation that may be concurrently imparted to the shaft by the motor.

The bearing assembly may be configured to accept the shaft in a throughbore thereof and may include at least one set of bearings, each of the bearings being supported in the bearing assembly to contact the surface of the shaft at determined angles relative to a longitudinal axis of the shaft so as to trace a helical pattern on the surface of the shaft as the shaft moves through the bearing assembly.

The at least one linkage arm at the second end of the shuttle arm may be rotatively coupled to the attachment end of the throttle lever, the at least one linkage arm being positioned parallel to the shaft to allow free movement of a distal end of the shaft as the bearing assembly moves along the shaft.

The system may be installed in an aircraft having two engines and the throttle lever of each engine may be controlled separately. In the event of an engine loss, the power setting of the remaining engine is controlled to stay above stall speed and is further controlled not to exceed an engine power threshold. The engine power threshold may be based at least in part on a maximum power imbalance that can be compensated by action of an aircraft rudder to prevent unwanted rotation of the aircraft.

According to one aspect of the invention, when an engine loss occurs, the autothrottle provides haptic feedback to indicate to the pilot whether throttle should be increased or decreased.

According to one aspect of the invention, the autothrottle enables full power usage during takeoff while monitoring engine balance and yaw.

According to one aspect of the invention, the autothrottle uses reduced power during landing, specifically an efficient level of power to stabilize the aircraft's approach.

According to one aspect of the invention, the autothrottle monitors ground speed and wind speed. If ground speed and wind speed are not equal, a controller of the autothrottle determines if a wind shear condition exists. If a wind shear condition exists, an alarm is activated and the autothrottle is disconnected. According to one aspect of the invention ground speed is determined using GPS.

According to one aspect of the invention a wind shear condition exists if ground speed and wind speed differ by at least 15 knots. Alternatively, or in addition, outside temperature can be monitored to determine if a wind shear condition exists. If the outside temperature decreases, the autothrottle can be disabled whereupon the pilot will resume control of the aircraft. Alternatively, or in addition, wind direction is monitored continually on field approach. An abrupt change in wind direction of speed indicates a wind shear condition. An abrupt change is a change in less than 30 seconds.

The disclosed embodiment also implements a method by which an autothrottle adjusts engine performance to substantially conform to preferred performance parameters. One or more sensors monitor engine performance. An engine controller, typically implemented with a microprocessor and memory uses data from the sensors to detect a condition wherein an actual engine performance differs from a preferred engine performance, referred to as a nonconforming condition. One such condition is a surge condition.

Haptic feedback is provided via a throttle lever until the actual engine performance matches the preferred engine performance. Preferably, the haptic feedback nudges the stick in the desired direction to correct the fault condition.

According to one aspect of the invention, the autothrottle is automatically engaged when a nonconforming condition is detected.

According to one aspect of the invention, a tension required to adjust the throttle lever(s) is increased or decreased based at least in part on the nonconforming condition.

According to one aspect of the invention the auto-throttle acts at and on power lever cables going to the engine. The autothrottle can also provide FADEC type engine protection. The actuator can be mounted on the engine at the cable attachment point. This adaptation has heretofore not been adapted because of the bulk of conventional auto-throttles and the high temperatures around the engine, especially after shutdown. The present implementation uses a stepper motor and therefore lends itself to remotely mounting the electronic control in a more moderate, nearby environment. The disclosed linear actuator has an instinctively safe clutch assuring manual override. The actuator shuttle would act directly on or near the power cable attachment to the fuel control valve. It will back drive the power lever in the cockpit. The stepper motor is mounted with the motor drive circuitry in the existing interface protection box. Additionally, an accordion protection sleeve is provided on the rotating drive shaft to protect it from oil and fluids contamination.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and/or other aspects and advantages will become more apparent and more readily appreciated from the following detailed description of the disclosed embodiments taken in conjunction with the accompanying drawings of which:

FIG. **1** is an elevated perspective view of an aircraft autothrottle operator and associated elements constructed in accordance with an embodiment of the disclosed invention;

FIG. **2** is a side view of the embodiment of the autothrottle operator depicted in FIG. **1**;

FIG. **3** is a perspective view of a second embodiment of the aircraft autothrottle operator with a housing cover removed;

FIG. **3**A is a partial perspective view of another embodiment of the aircraft autothrottle operator;

FIG. **4** is an enlarged view of the bearing assembly and shaft of the embodiment of the autothrottle depicted in FIG. **3**;

FIG. **5** is a side view of the embodiment of the autothrottle operator depicted in FIG. **3**;

FIG. **6** is a flow chart illustrating a method for operating an autothrottle system for an aircraft; and

FIG. **7** is a schematic representation of a segment of a flight path.

DETAILED DESCRIPTION

The disclosed autothrottle is configured to move an aircraft's power throttles using independent linear actuators, typically located in the throttle quadrant and commonly attached to the throttle power handle at its connection to the throttle cable. According to one aspect of the invention, an actuator functions by rotating a hardened, precision ground, and polished stainless steel shaft that carries an actuation shuttle, which is the heart of the throttle control. The actuation shuttle typically carries two sets of three precision ball bearings mounted at a rotation axis angle relative to the shaft axis. The outer races of the bearings roll on the shaft, moving the shuttle along the shaft at a rate proportional to the shaft diameter and the bearing axis angle. The shuttle's thrust is proportional the coefficient of friction between the outer race of the spring loaded ball bearings and the shaft. The shuttle moves accurately along the shaft, much like a threaded lead-screw, but without the threads. It slips at a very repeatable thrust force that is proportional to the spring tension in the bearing carrier. This controlled breakaway force assures that the flight crew can maintain backlash-free control of the engine power even with a catastrophic malfunction of any of the actuator's components and without having to disengage a clutch. Under manual operation, the throttles cause the shuttle to rotate the brushless motor. This requires precise sequencing of the stator winding to rotate, thereby obviating a drive motor runaway.

An autothrottle computer monitors the engine internal temperature, the turboprop's torque or EPR/N1 in a turbofan engine, gas generator speed, prop speed, air data, GPS position, GPS velocity, battery voltage, and the like. The autothrottle computer uses this data to control the thrust and protect the engines from damage. The power lever controls the engine thrust to control speed while maintaining safe speeds and safe temperatures.

The autothrottle has various operating modes including at least a takeoff mode, a climb mode, an airspeed hold mode, one or more protection modes, an engine out mode, an automatic speed selection mode, a simultaneous speed mode selection, and a windshear sense.

In takeoff mode, the throttles are advanced to a predetermined thrust, or optionally based on alternative limiting factors to a different thrust. The computer monitors the engine power as the throttles are advanced. The command is reduced if the engine starts to surge or exceed the thrust/torque limit due to ram air.

In climb mode, the throttles are maintained at maximum torque/thrust for the maximum allowed time, typically 3-5 minutes. The throttles are then automatically reduce to a maximum continuous climb or torque schedule (PWC) as a function of altitude. In this mode, the aircraft autopilot's SPEED-ON-ELEVATOR can be engaged. The autothrottle protects the engine from over temperature and/or over torque. As the aircraft climbs to higher altitudes, the temperature (TIT) will increase and the temperature protection mode will become active. The temperature protection mode adjusts thrust to limit the temperature to a maximum continuous temperature. The climb thrust is maintained as the aircraft levels off at cruise altitude or until commanded to change value or Mode.

The airspeed hold mode controls airspeed to at a commanded or preset value by a manual mode selection change or automatically by an FMS. The autothrottle will maintain the selected airspeed through climb or descent, except as may be limited by maximum torque, temperature, or altitude rate. The autothrottle can be enabled to limit IAS to 250 knots below 10,000 feet, automatically based on GPS location. The airspeed can be set by an FMS airspeed input, which facilitates RTA and RNP operations that require multiple speed changes. The control computer can be configured to automatically set approach speeds based on aircraft gross weight. In addition, commanding missed approach with a TOGA button can automatically set TO/GA thrust while maintaining engine protection.

Various protection modes are constantly monitoring aircraft performance and engine performance. The engines are monitored and limited to the established safe torque and temperature limits. The airspeed is controlled at both under-speed and over-speed including VMO/MMO. Additionally, the AOA can be monitored. The autothrottle can also be configured to compensate for bank angle at low airspeeds.

An engine out mode (Vmca mitigation mode) monitors for a loss of an engine (OEI) on a multiengine aircraft, which can result in hazardous yaw at speeds below Vmca. The autothrottle computer continually monitors multiple engine parameters and will detect a loss of engine by triggering on: N1 (compressor turbine) nominally below 40% and oil pressure nominally below 10 psi with auto-feather active. The computer computes the amount of rudder authority loss due to the reduction of airflow over the rudder. Vmca is the minimum control speed in the take-off configuration, a.k.a. air minimum control speed or minimum control speed in free air.

Haptic throttle handle vibration is used to alert the flight crew with OEI and IAS below Vmca, if a thrust of a remaining engine exceeds a Maximum Allowable Thrust. A body rate yaw sensor detects an onset of adverse yaw and will initiate the haptic crew alert to provide an additional margin of safety to compensate for weight or configuration. The haptic vibration is direction sensitive, such that it will increase the force necessary to further advance the throttle in over speed, over-torque or over-temperature. The haptic vibration can be configured to hinder further advance and deliberately retard the throttles until the exceedance is cleared. Also, the throttles will be hindered from further reduction with an under-speed or AOA warning and deliberately advance to eliminate an impending hazardous condition.

An automatic thrust control may be user enabled in takeoff mode that is initiated by a loss of an engine, with the airspeed below Vmca+3 knots. This automatic control will retard the operating engine to a defined thrust/. The computer will monitor a yaw input and if the yaw exceeds 5 degrees when in OEI and at or below VMCa+3 IAS, the computer reduces the thrust of the good engine to mitigate the yaw.

Automatic speed selection can be user activated to automatically set the appropriate Maneuvering speed for turbulence penetration and/or Vref for approach speeds based on gross weight. It should be noted that a simultaneous speed mode selection of the autothrottle and Autopilot speed hold is not permitted. If the autothrottle detects simultaneous attempts to control speed-on-elevator, the autothrottle will disconnect and the pilot will receive an alert. The alert can be a visual and/or a speaker/headphone audio alert.

Finally, windshear sense is an algorithm that monitors ground speed (GS) versus airspeed (IAS) and ambient temperature (SAT). When the aircraft is in landing configuration with gear and flaps deployed, a rapid increase of IAS vs GS disconnects the autothrottle to prevent automatic thrust reduction. The disconnect alerts the flight crew with an audio and/or visual alert.

FIGS. **1** and **2** present two views of an embodiment of the precision aircraft autothrottle operator. The autothrottle operator system or arrangement, identified in the drawing figures by the general reference numeral **10**, is attached for use to a conventional throttle handle or lever **12** of an aircraft. The throttle lever **12**, the configuration and construction of which is conventional, is mounted for pivoted movement or displacement about a shaft or other pivot point or fulcrum **14** at which the lever **12** is secured in place at the throttle quadrant (not shown) of the aircraft. The distal end **16** of throttle lever **12** is configured for ease of grasping and manipulation, to advance and retard the lever **12** through its arcuate range of displacement, by a pilot manually controlling the power output of the associated aircraft engine and, thereby, the airspeed or velocity of the aircraft. The opposite or proximal end **18** of throttle lever **12** connects at attachment pin or shaft or point **20** at one end of a cable **22** that itself connects, generally at its far end, to the engine or engine controller associated with lever **12**. Thus, pilot manipulation, i.e., counterclockwise (in the figures) advancement or clockwise retarding—of the lever distal end **16** about pivot point **14** causes opposite-sense arcuate motion of attachment point **20**, thus effecting linear displacement of cable **22** and corresponding changes in the power output of the associated engine. Aircraft implementations in which the motion-transmitting functionality of cable **22** is instead provided by other elements or systems are known in the art, but changes in the power or thrust generated by an aircraft engine are in any event generally controlled in accordance with sensed displacement of the proximal extension of the corresponding throttle lever.

The autothrottle operator of the embodiment depicted in FIGS. **1** and **2** is formed by an actuator assembly **24**, a motor **26**, and a position sensor **28**.

In particular implementations, actuator assembly **24** comprises an arrangement formed of a bearing assembly **30** (also referred to herein as shuttle body **30**), an elongated shaft **32** and a linear fork **34**.

The combination of bearing assembly **30** and shaft **32** function to convert rotary motion into linear displacement. In the embodiment depicted in the figures, this functionality is implemented using a commercially-available assembly identified by its manufacturer, Zero-Max, Inc. of Plymouth, Minn. as a Roh'lix Linear Actuator. Six rolling-element bearings **36**, in sets of three, are supported in a base block **38** at predetermined angles about a throughbore **40** defined in block **38** and through which shaft **32** extends for longitudinal displacement of block **38** along the shaft (a more detailed view of the block **38** and shaft **32** can be seen in FIG. **4**, which is discussed below in the context of the second embodiment). Each of the bearings **36** contacts the surface of shaft **32** at an angle, such that the bearings **36** trace a helical pattern along the shaft and thereby longitudinally displace block **38** along the shaft as the shaft is rotated. Put another way, as the shaft **32** is rotated, i.e., by selective operation of motor **26**, the bearings **36** trace out an imaginary screw thread, causing linear longitudinal displacement of block **38** on and along shaft **32**. Base block **38** is constructed as two halves that are coupled by the combination of springs **42** and associated screws **44** that are adjusted to selectively setting the thrust force that bearings **36** apply to and against shaft **32** and, correspondingly, the amount of linear force that must be manually applied to the block **38** to overcome the thrust force and allow the bearings **36** to slip longitudinally along the surface of shaft Thus, when the thrust forces set or provided by a predetermined adjustment of screws **44** are exceeded, block **38** slips on and along shaft **32** irrespective of any rotation that may be concurrently imparted to the shaft by, e.g., motor **26**.

With continued reference to FIGS. **1** and **2**, the operatively-rotated shaft of motor **26** is coupled to the end of shaft **32** remote from block **38**. The motor **26** may be, for example, a precision stepper motor that steps in response to the input of pulses or other electrical signals from a diagrammatically-depicted controller **48** through **200** consecutive rotative positions spaced about 1.8 degrees apart. Motor

26 is operable to incrementally (i.e., step-wise) rotate bidirectionally, i.e., selectively in both/either the clockwise and/or counterclockwise directions, based on the operating signals from controller **48**. One or more gears may optionally between the motor shaft and shaft **32** if needed or desired to attain a rotational speed of shaft **32** deemed suitable for the particular implementation and/or aircraft. Motor **26** is mounted on a motor bracket **46** having an opening **47** for unimpeded passage of shaft **32** and/or the motor shaft, bracket **46** being itself securable to a fixed structure in the aircraft cockpit to secure the motor **26** against movement as it operatively rotates shaft **32**.

Controller **48** may by way of illustration comprise an electronic controller having a processor and memory dedicated to the operation of motor **26** and, optionally, also to associated elements and functionality of the inventive autothrottle system, or its functionality may be incorporated in or as a part of the control system or elements of an autopilot system or of a flight management system or of other avionics and/or automation systems of the aircraft.

Linear fork **34** connects shuttle block **38** to throttle lever attachment point **20**. Fork **34**, which may be implemented as a unitary element (as described below in the context of the second embodiment), comprises in the illustrated embodiment a shell or tray **50** to which block **38** is secured, a pair of opposed linkage arms **52** that are rotatively coupled at one of their ends to attachment point **20** of the throttle lever, and a web **54** that joins tray **50** to arms **52**. The free end portion **56** of shaft **32** that is opposite its coupled connection to motor **26** is freely movable through and relative to apertures, passages and voids and the like that are defined in web **54** to accommodate the shaft end **56** as shuttle block **38** is operatively displaced or "shuttles" along shaft **32**.

The current relative displacement or position of shuttle block or body **38** along the elongation of shaft **32** is determined by monitoring changes in the distance or spacing between, by way of illustration, the positionally-fixed motor **26** and the movable shuttle body **38**. To provide this functionality, in the illustrated embodiment the position sensor **28** is implemented by a linear potentiometer **58**, such as, for example, an MLP miniature linear potentiometer manufactured by Celesco Transducer Products, Inc. of Chatsworth, Calif., that is connected as a position sensor between motor bracket **46** (to which the motor is secured) and tray **50** (on which the shuttle body is mounted). Potentiometer sensor **58** is electrically connected to controller **48** which thereby monitors changes in the linear position of shuttle body **38** (and thus, correspondingly, of the attachment point **20** at the proximal end of the throttle lever) on and along shaft **32**. The throttle position is accurately mapped and recorded using the potentiometer sensor **58** when the system is installed in the aircraft. Because the linear actuator is controlled with a stepper motor, a map of the throttle position for an individual step is determined and used as a means of detecting uncommanded movement or slip in the movement due to obstruction of the throttle lever. In particular embodiments, such detection could ultimately result in the system disengaging the autothrottle.

FIGS. **3-5** depict a second embodiment of the aircraft autothrottle operator. In this embodiment, the shuttle block **38** is connected to the throttle lever attachment point **20** by a shuttle arm **34'** which is implemented as a unitary element, rather than a dual-pronged fork **34**, as discussed above (the controller **48** is not shown in these views). The shuttle arm **34'** has a shell or tray **50'** at one end thereof to which block **38** is secured. The tray **50'** is oriented so that a mounting surface of the bearing assembly **30** is oriented in a vertical plane, whereas in the first embodiment, the mounting surface is oriented in a horizontal plane. The motor **26** may be held in place at a pivoting joint of a bracket **41** which can be attached to an interior structure of an aircraft. A detailed view of the block **38** and shaft **32** can be seen in FIG. **4**. In FIG. **3**, the cover of the housing **39** containing the block **38** is not shown so that the block **38** can be seen in the figure. FIG. **5** shows the housing **39** with its cover in place. At the distal end of the shuttle arm **34'** is a linkage arm **52'** which is rotatively coupled to attachment point **20** of the throttle lever. The distal, i.e., free end portion **56**, of shaft **32** that is opposite its coupled connection to motor **26** is parallel to the linkage arm **52'** and therefore can move freely as shuttle block **38** is operatively displaced or "shuttles" along shaft **32**.

In operation, the autothrottle System requires a throttle position signal from a throttle position sensor. As discussed above, the sensor is a linear potentiometer that is read by analog to digital converter in the Engine data concentrator. In one embodiment, a very precise optical position sensor can replace the linear potentiometer. The optical position sensor uses a laser beam projected on a white target that is monitored by a photo diode array. The diode array sensor uses triangulation of the position of the target relative to the source and sensor, to determine throttle position. The non-contact implementation of this optical sensor eliminates a risk of obstruction of movement of the throttle levers. The basic actuator mechanism is, by its nature, not subject to malfunction that would lock up the throttle.

In the alternative embodiment shown in FIG. **3**A, an optical sensor is used in place of the linear potentiometer **58**. Alternatively, both the optical sensor and the linear potentiometer can be used to provide redundancy. The current relative displacement or position of shuttle block or body **38** along the elongation of shaft **32** is determined by monitoring changes in the distance or spacing between, by way of illustration, the positionally-fixed motor **26** and the movable shuttle body **38**. To provide this functionality, in the illustrated embodiment the position sensor is implemented by an optical distance sensor having a transmitter **28**B and an receiver **28**C, such as, for example, a CMOS distance measuring sensor that is connected as a position sensor to measure a distance between motor **26** and tray **50'** (on which the shuttle body is mounted). Alternatively, the optical distance Sensor can be mounted to the motor bracket **41**. In a preferred embodiment, a reflector is mounted to the tray **50'** or another suitable component.

One skilled in the art would appreciate that the locations of the elements can be reversed so that the transmitter **28**B and receiver **28**C are arranged at the tray **50'** and the reflector is arranged at the motor **26**, the motor bracket **41**, or another suitable component. The optical sensor **28**B, **28**C is electrically connected to the controller **48** which thereby monitors changes in the linear position of shuttle body **38** (and thus, correspondingly, of the attachment point **20** at the proximal end of the throttle lever) on and along shaft **32**. The throttle position is accurately mapped and recorded using the optical sensor **28**B, **28**C when the system is installed in the aircraft. Because the linear actuator is controlled with a stepper motor, a map of the throttle position for an individual step is determined and used as a means of detecting un-commanded movement or slip in the movement due to obstruction of the throttle lever. In particular embodiments, such detection could ultimately result in the system disengaging the autothrottle.

The basic manner of operation of the inventive autothrottle operator **10**, to selectively control an aircraft throttle in an automated operating mode (e.g. under the control of an autopilot system), will now be described. In response to electrical signals from controller **48**, stepper motor **26** is operated to selectively rotate coupled shaft **32** in a desired direction (to respectively increase or decrease engine thrust) and, as shaft **32** rotates, shuttle body **38** is linearly displaced along and relative to shaft **32** as the bearings **36** trace a helical path along the surface of rotating shaft **32**. This linear displacement of shuttle body **38** is transferred through linkage fork **34** to throttle lever **12** at attachment point **20**, causing throttle lever **12** to pivot about its fulcrum **14**, just as though throttle lever **12** were being manually moved about fulcrum **14** by a pilot grasping its distal end **16**. The resulting displacement of attachment point **20** at the proximal end **18** of throttle lever **12** likewise causes linear displacement of engine control cable **22**, thus causing the engine to vary the power output or thrust of the aircraft engine associated with that throttle lever. Thus, as shuttle body **38** is displaced along shaft **32** toward motor **26**, throttle lever **12** is rotated counterclockwise (in the Figures) to reduce engine power and, as shuttle block **38** is displaced along shaft **32** away from motor **26**, throttle lever **12** is rotated clockwise to increase engine power—again, just as though the throttle lever were being manually adjusted by a pilot grasping the throttle lever at its distal end **16**.

Changes in the linear position of shuttle body **38** relative to motor **26**—and, correspondingly, of the rotative position of the throttle lever **12**—can be determined by controller **48** by monitoring the output of the potentiometer position sensor **58**, as can the current position of the shuttle body. However, since it is the function of an autothrottle to vary engine output power to, for example, attain and/or maintain a predetermined airspeed, controller operation of motor **26** to increase or decrease engine power is dependent not so much on the absolute position or relative spacing of shuttle block **38** and motor **26** but, rather, on whether an increase or decrease in engine power (and, thus, whether operation of motor **26**) is needed to provide the desired airspeed; accordingly, monitoring of the output of position sensor provides feedback to controller **48** for use in, inter alia, confirming proper operation of the autothrottle system.

An important and highly advantageous feature of the inventive autothrottle system **10**, as compared to conventional commercial autothrottle arrangements, is the provision of override capabilities without the use of clutches and their associated apparatus and connections. The capability of the inventive system **10** to be easily overridden for manual pilot control of the throttle(s), when the system **10** is engaged and even while it remains so, is an important and inherent feature of the system **10** and its construction. By physically grasping throttle lever **12** at its distal end **16** and applying sufficient force to advance or retard the throttle, shuttle body **38** is caused (by its coupled connection to the proximal end **18** of lever **12**) to slip or slide longitudinally along shaft **32**, thus providing manual pilot control of the throttle even if controller **48** were to remain operationally activated to effect rotation of the motor and shaft **32**. Of course, it is generally intended that, when manual manipulation of throttle lever **12** is initiated, autothrottle controller **48** will normally be, automatically deactivated from continued operation of motor **26**, but the ability to readily assume manual control of the throttle in the event of, for example, a systemic or component failure to easily and immediately override the autothrottle functionality presents a particularly noteworthy improvement in assuring failsafe operation of the aircraft.

As previously described, pilot-effected manual override of the autothrottle arrangement requires that the pilot advance or retard the throttle lever **12** with a force that, at a minimum, exceeds the thrust force that the bearings **36** apply to the surface of shaft **32**. Since that thrust force is adjustable by selective rotation of adjustment screws **44** of shuttle body **38**, in particular implementations of the inventive arrangement the thrust force is preset to assure that manual override by the pilot is readily available using a reasonable magnitude of pilot-applied force that is deemed suitable for the particular application and for assuring continued safe operation of the aircraft. Setting of the bearings thrust force to a magnitude sufficient to assure linear movement of shuttle body **38** along and in response to rotation of shaft **32** will provide both reliable automated autothrottle control of the throttle and manual override control using reasonable pilot-applied forces on the throttle lever.

For example, a stepper motor contemplated for use in the inventive autothrottle assembly operatively generates a fairly high torque that rotates the shaft **32** to produce, for example, about 12 pounds of torque on the engine throttle control cable **22** (i.e., at the proximal end **18** of throttle lever **12**) and about 4 to 6 pounds of force at the distal end **16** of throttle lever **12**. This means that, in a typical intended implementation of the system **10**, the aircraft pilot can easily override the autothrottle simply by pushing or pulling back, with a force of at least the same 4 to 6 pounds, on the distal end **16** of the throttle lever even if the motor **26** is engaged and operatively rotating the shaft **32** and/or even if the entire assembly is frozen. By manually applying to the throttle lever a force of about or in excess of, e.g., 4 to 6 pounds—which is a relatively small amount not appreciably greater than the force required to manually adjust the throttle lever without an engaged autothrottle—the shuttle body **38** will slip on and longitudinally along shaft **32** whether or not the shaft is being rotated by motor **26** and the pilot will thereby immediately obtain full, unconstrained and unconditional manual control of the throttle. The autothrottle arrangement thus presents an inherently safe system that assures a pilot the ability to readily assume manual control of the aircraft throttle(s) at any time. When combined with or forming an element of an aircraft autopilot system, the autothrottle arrangement **10** provides an intrinsically safe ability to quickly and easily override the forces applied by the autothrottle controller and the autopilot—instructed operations.

The inventive autothrottle arrangement can also be implemented to provide a warning to a pilot in the event that the aircraft is determined to be operating, for example, at too high or too low an airspeed for the current operating conditions or maneuvers of the aircraft. As is known, stepper motors such as the motor **26** generally contemplated for inclusion in the system **10** have (e.g.) three coils which are, in normal use, selectively actuated to cause the motor to bidirectionally rotate its shaft from step to step. In accordance with this embodiment, haptic feedback can be applied to the throttle lever, i.e., in the nature of "stickshaker" functionality—when the controller **48** determines, e.g. by monitoring at least the aircraft airspeed, that the airspeed is approaching the bounds or limits of a predetermined range of values.

Thus, if the controller **48** determines that the aircraft's increasing airspeed is approaching a predetermined safety limit value (e.g. the maximum structural cruising speed of the aircraft), or that its decreasing airspeed is approaching a predetermined minimum limit value (such as the minimum controllable airspeed or stall speed of the aircraft), motor **26** can be operated to cause the throttle lever to oscillate or shake and thereby alert the pilot to the impending unsafe overspeed or underspeed condition. Similarly, by monitoring engine torque, controller **48** can likewise provide a warning to the pilot by applying like haptic feedback through the throttle handle **12** if it is determined that the engine is at or approaching an unsafe operating condition, e.g. excessive torque.

This functionality is implemented by selectively applying electrical signals to individual ones or combinations of the multiple actuating coils of the motor, for example by activating only two of the three coils, or rapidly cycling electrical signals to a selected one or more of the motor coils-and does not require that, at the time of such haptic warning, the autothrottle must be or have been engaged or active to autocontrol the throttle and, thereby, the engine power. Thus, for purposes of this pilot-warning functionality the inventive autothrottle system **10** provides "always-on" sensing and haptic alert capabilities. In any event, if controller **48** senses that no manually-input changes to the position of throttle lever **12** have been applied in response to its haptic warning, the system **10** can be configured to operatively adjust the engine power or torque to correct the airspeed or overtorque condition by suitable motor-driven rotation of shaft **32** and the resulting linear displacement of shuttle body **38** as explained hereinabove.

Accordingly, by implementing this functionality the system **10** can be viewed as always engaged, with controller **48** continuously monitoring relevant characteristics and operating conditions of the aircraft that may warrant or necessitate a warning—delivered with haptic feedback delivered by shaking or oscillating or vibrating the throttle lever **12** and/or the initiation of automated controlled movement of the throttle lever by operation of motor **26** to correct or ameliorate the out of bounds condition.

Another advantageous feature of the inventive autothrottle arrangement is realized in an aircraft having, for example, two (or more) throttle levers each controlling the power output of a corresponding engine. In such multi-engine aircraft, manual control of airspeed, through manipulation of the throttle levers, is effected by concurrently advancing (or retarding) the two (or more) throttle levers. An issue that can arise in manual pilot control of the throttles of such multi-engine aircraft is that if the multiple throttle levers are not adjusted together, i.e., so that each lever is advanced or retarded by about the same amount, the engines may produce different levels of power or torque, as a result of which the propulsion of the aircraft may be unbalanced with one engine producing more thrust or torque than another, as the engine on one wing is producing less (or more) thrust than the engine on the other wing. Similarly, operating characteristics of one engine, with respect to another engine of the aircraft, may result in each engine generating different amounts of thrust or torque even if the respective throttle handles are correspondingly positioned or adjusted.

In a multi-engine aircraft in which an inventive autothrottle system **10** is provided for each of the engines, an imbalance of the thrust or torque produced by the two (or more) engines can be sensed and used by the controller(s) **48** to warn or alert the pilot of the imbalance by haptically shaking or vibrating (or the like) one or both/all of the throttle levers, using the procedure described hereinabove. As previously noted, this functionality does not require that the autothrottle system **10** be in operational use to autocontrol the positions of the throttle levers and, correspondingly, to automatically vary or adjust the thrust or power output of the engines. In addition, as also described above, the system can be configured so that detection that the multiple engines are out of sync or not generating the same levels of thrust or torque will cause the autothrottle system **10** of one or more of the engines to automatically readjust the corresponding throttle lever(s) **12** and thereby equalize the relevant operating characteristics of the multiple engines.

Another advantageous application of the inventive autothrottle arrangement in multi-engine aircraft is warning of and preventing the application of too much thrust to, for example, one of the two engines when one engine fails or is otherwise determined to be generating less than the intended, or expected, thrust. In a (by way of illustrative example) two engine aircraft, the manufacturer will have established an airspeed, VMCA, as the minimum controllable airspeed on a single engine when the aircraft is airborne, i.e., the minimum airspeed at which, with only one of the two engines operating, the pilot will have sufficient rudder authority to prevent the aircraft from yawing to an extent that will cause the aircraft to, in effect, roll over and dive into the ground. Thus, the failure—or degraded performance—of one engine in flight creates an asymmetric thrust condition requiring that the pilot of a multi-engine aircraft immediately level off, apply significant rudder and increase power to the remaining engine to maintain an airspeed at or above VMCA. And where the aircraft airspeed is, when one engine fails, below VMCA—such as in the landing phase of flight when engine power is generally brought back to a fraction of full power or thrust—the application of too much power to the engine that remains in operation will create a dangerous asymmetry in thrust and adverse yaw from which the application of rudder may not enable a safe recovery.

Accordingly, in this further use of the inventive autothrottle arrangement, controller **48** monitors (at least) the current airspeed (and, preferably, the acceleration) of the multi-engine aircraft and continuously calculates, for single engine operation, the maximum safe or allowable thrust that should or can be placed on the remaining engine under current flight and operating conditions. Put another way, the controller **48** continuously calculates, for the current airspeed below VMCA, the allowable power limit (i.e., the maximum safe or permissible generated thrust) for the remaining engine for that airspeed. If the power or thrust being produced by that remaining engine, in accordance with the position of throttle lever **12**, is increasing and approaching (or at or beyond) the calculated maximum thrust that the engine should be permitted to produce at the current airspeed, an alarm or warning will be generated by the inventive arrangement **10** by vibrating or oscillating the engine's throttle lever **12** (as described hereinabove) to alert the pilot of the impending or existing over-throttle condition.

If the position of throttle lever **12** is not manually adjusted by the pilot in response to the alert, then the motor **26** of the inventive autothrottle arrangement **10** may under appropriate conditions be operated to adjust the position of the throttle lever (and thus retard the throttle) under control of the system **10**, without pilot input and irrespective of whether the autothrottle system **10** had theretofore been operatively controlling the aircraft throttles, and thereby avoid or terminate the over-throttle condition of the operating engine.

This functionality can also be applied to assist the pilot in manually advancing the throttle, in response to the failure of the other engine, by only that amount appropriate to avoid an over-throttle condition of the remaining engine, by providing haptic feedback (by vibrating or oscillating the throttle lever **12**) as the allowable thrust limit for the engine is approached; the pilot can proceed to manually advance the throttle lever until it starts to vibrate and, as the aircraft airspeed begins to increase, continue to manually advance the throttle lever until, again, the autothrottle system **10** resumes vibration of the throttle lever. Since the controller **48** is continuously calculating and determining an increasing maximum allowable engine thrust as the airspeed increases, the pilot can continue to manually adjust the throttle lever **12** in accordance with the vibration, or lack thereof, applied to the throttle lever by the autothrottle system **10**. In this manner the pilot is continuously guided in manually adjusting the throttle so that the engine is always operating to generate the maximum safe thrust based on the current airspeed and other relevant flight and environmental factors that the controller **48** can monitor.

For this and other implementations and applications of the inventive autothrottle system, the system can itself adjust or vary or scale the magnitude of such haptic vibrations or oscillations of the throttle lever as a function of the urgency of the need for pilot action—so that, for example, the system applies relatively small magnitude vibrations to the throttle lever as the limit value of airspeed or thrust or the like is first approached, with vibrations of increasing magnitude applied to the throttle lever as the limit value continues to be approached and is reached or exceeded.

Accordingly, by implementing this functionality the system **10** can be viewed as always engaged, with controller **48** continuously monitoring relevant characteristics and operating conditions of the aircraft. By, for example, such monitoring, the inventive autopilot system is additionally configured to provide additional advantageous modes of operation, as set forth below.

For example, the system **10** may be configured to provide a Speed Hold Mode. In the speed hold mode the system **10** adjusts the engine thrust to achieve and maintain the selected airspeed.

The system **10** also may be configured to provide a Torque Control Mode, in which the system **10** is configured to adjust the engine thrust to achieve and maintain the selected engine torque.

The system **10** also may be configured to provide a Temperature Limit Control Mode. In this mode, the engine thrust is adjusted to achieve and maintain the selected engine turbine inlet temperature.

The system **10** also may be configured to provide an Engine Protection mode in which the system **10** will adjust engine thrust to keep engine torque, speed and temperature from exceeding pre-defined targets in all modes of operations. In particular embodiments, the autothrottle may be configured to protect the engine from exceeding the limits for one or more of the following: torque, shaft horsepower, engine and propeller speeds, engine temperature, engine pressure ratio.

The system **10** also may be configured to provide a Speed Protection Mode. In this mode, at all times the autopilot system protects the aircraft from over-speed or under-speed by adjustment of the engine thrust.

The system **10** also may be configured to provide a mode in which, during manual manipulation of throttles, if the throttles are moved too rapidly by the pilot such that it could result in an engine power surge, the autopilot mechanism provides a warning to the pilot, e.g., by vibrating the throttle lever.

The system **10** also may be configured to provide a turbulence penetration mode that, when engaged by the pilot, automatically adjusts the power to achieve a turbulence penetration speed calculated based on gross weight and aerodynamic characteristics of the aircraft.

The system **10** also may be configured to provide a mode in which approach and take off speeds are calculated and entered into the speed control mode of the autothrottle. Landing approach speed is typically calculated as a function of gross weight and stall margin and may also include factors such as, for example, wind speed and flap configuration. The system **10** may also calculate and control airspeed to maintain optimum Lift over Drag (L/D), e.g., by using an average Angle Of Attack (AOA) from the aircraft AOA sensor.

The system **10** also may be configured to provide multiple autothrottle modes, such as, for example, automatic, airspeed control, and angle of attack control. In automatic mode, the autothrottle flies the airplane at maximum speed by controlling to the torque limit during initial take off and climb until the temperature becomes critical, at which point the autothrottle controls the engine to the maximum allowed temperature. In particular embodiments the autothrottle may be configured to protect the aircraft from out of limit conditions for one or more of the following: minimum airspeed; maximum angle of attack; and maximum airspeed under normal and turbulence conditions.

The system **10** also may be configured so that when it is installed with an engine that has no protection mechanism such as a full-authority digital engine control (FADEC), the autopilot monitors critical engine parameters, such as, for example, temperature, speed pressure ratio, torque, horse power, etc., and acts to prevent these parameters from exceeding the maximum values.

The system **10** also may be configured so that in the event of an engine power loss in a two engine aircraft, the autopilot manages the power setting of the remaining engine to stay above stall speed. At the same time the system controls the remaining engine to maintain safe operating conditions. In one embodiment, in the event of engine loss the throttle lever for the stalled or inoperative engine will vibrate or provide other haptic feedback to the pilot that the subject throttle lever has no effect.

In one embodiment, the autothrottle addresses a problem occurring from gas generator surges during throttle increase; which is a problem occurring, for example, on Pratt & Whitney turboprops. Specifically, the autothrottle tailors throttle lever performance and response to match or substantially correspond to an ideal or preferred engine performance curve. The autothrottle can be configured to monitor conditions and provide haptic feedback, assume control, be disengaged, or the like.

For turboprops, the prop is turned by blowing hot gas over a turbine. Sudden throttle increase may cause gas generator surges, which causes uneven engine performance. Thus, the throttle needs to be delicately increased to alleviate this problem, according to one aspect of the invention, the autothrottle will automatically resist pilot manipulation of the throttle lever based on monitoring of engine performance and other parameters, thereby making it more difficult for manual control of the throttle lever until an existing gas surge dissipates. It should be noted that the autothrottle will provide haptic feedback or automatically increase throttle lever response if the throttle lever is moved too slowly. If a gas surge condition is detected and the autothrottle is not yet engaged, the autothrottle will automatically engage to counteract the surge condition. Alternatively or in addition, the autothrottle will provide a haptic warning such as vibration of the throttle lever when a surge condition is detected without engaging the throttle.

More particularly, the autothrottle feature will control an increase in the throttle in a regulated manner. This is helpful because the response of the engine is nonlinear such that small increases or decreases of throttle level result in relatively large and disproportionate power changes. Thus, by "mapping" the power performance of the engine and then using that information for throttle control, the throttle can be automatically controlled to optimally perform over the different regions of the engine's power output performance curve. For instances in which the autopilot is not engaged, as the engine performance deviates from the preferred performance curve, the autothrottle will provide haptic feedback to the pilot via the throttle lever to signal to the pilot to adjust the throttle until the throttle engine performance is bought back into alignment with the preferred performance curve of the engine.

In one embodiment, the autothrottle will automatically retard the lever motion to scale the lever motion based on a monitoring of the engine until the gas surge dissipates. In one embodiment, the midrange is slowed down until the surge dissipates. Alternatively, if the autothrottle is not engaged or an autothrottle override is engaged, haptic feedback is provided until the surge condition dissipates. Typically, this situation arises during landing, specifically during a landing abort. When landing is aborted and the aircraft has to make another attempt, the power needs to be increases quickly. However, this will create a power surge which can lead to temporary engine failure. The autothrottle will control the power increase in a regulated manner and engage in high stress situations, such as an aborted landing attempt. A mapping of throttle position and power identifies the problem issues and regulates the response to avoid surge conditions.

In one embodiment, as the engine performance deviates from the performance curve the autothrottle increases or decreases lever tension as required to make the throttle lever easier or harder to adjust so that the engine performance returns to an optimal point on the performance curve. Additionally or alternatively, when the engine performance deviates from the performance curve, a haptic or other warning is provided. Additionally or alternatively, the autothrottle can be automatically engaged or disengaged.

In an aircraft in which an inventive autothrottle system **10** is present, a surge can be sensed and used by the controller (s) **48** to warn or alert the pilot of the surge by haptically shaking, vibrating, or the like, of the throttle lever(s), using the procedure described hereinabove. As previously noted, this functionality does not require that the autothrottle system **10** be in operational use to autocontrol the positions of the throttle levers and, correspondingly, to automatically vary or adjust the thrust or power output of the engines. Rather, the system can be configured so that detection of a surge will cause the autothrottle system to automatically adjust the corresponding throttle lever(s) **12** to control the relevant operating characteristics of the engines. Alternatively, the system can be configured so that detection of a surge will cause the autothrottle system to provide haptic feedback to the corresponding throttle lever(s) **12**.

The application of the inventive autothrottle arrangement provides warning of and substantially prevents the surge condition. Controller **48** monitors (at least) the current airspeed (and, preferably, the acceleration) of the aircraft and continuously calculates the maximum safe or allowable thrust that should or can be placed on the engine under current flight and operating conditions. In other words, the controller **48** continuously calculates, for the current airspeed below VMCA, the allowable power limit (i.e., the maximum safe or permissible generated thrust) for the engine for that airspeed. If the power or thrust being produced by that engine, in accordance with the position of throttle lever **12**, is increasing and approaching (or at or beyond) the calculated maximum thrust that the engine should be permitted to produce at the current airspeed, an alarm or warning will be generated by the inventive arrangement **10** by vibrating or oscillating the engine's throttle lever **12** (as described hereinabove) to alert the pilot of the impending or existing surge condition.

FIG. **6** is a flow chart for method for operating an autothrottle system for an aircraft. The method includes monitoring engine performance of an aircraft engine (S**10**). When a gas surge is detected (S**20**), the autothrottle system is automatically engaged (S**30**). In one embodiment, the monitored engine performance is compared to a power performance curve of the aircraft engine (S**40**). The autothrottle provides haptic feedback to an aircraft pilot via a throttle lever until the monitored engine performance matches the preferred engine performance (S**50**). According to one aspect of the invention, the haptic feedback comprises increasing or decreasing a throttle lever tension. The autothrottle manipulates the throttle lever in a regulated manner until an existing gas surge dissipates (S**60**). The manipulating of the throttle lever is based on the monitoring of engine performance until the existing gas surge dissipates.

It should be noted that the disclosed autothrottle can be used with FADEC (Full authority digital engine control) engines. Using haptic feedback the autothrottle is configured to drive the motor two small steps, about twelve thousandths of an inch, against the motion that is going to cause a fault condition or an out-of-limits condition and then one step back so that the throttle actually progresses against the pilot's manual motion. The throttle control will vibrate and actually push against the pilot. The pressure is not so strong that it cannot be overridden, if necessary. However, the autothrottle is configured to actually pushes back and move the throttle, slowly, moderately, to restore an in-limits condition.

In one embodiment, haptic feedback is used to alert the pilot when he is in V/MC (velocity for minimal controllable air speed) location mode. On approach the pilot would feel a vibrating in his throttle handle and retard the throttle until the vibration stops. Once the vibration stops, the throttle can be advanced until it starts vibrating then back it off a little bit. The same thing he could use in takeoff because a pilot can push the throttle forward and then if he starts getting close to the V/MC point it would vibrate and he would draw it back until the vibration stops. Alternatively, can the autothrottle can engage automatically.

As discussed in more detail below, the autothrottle wind shear detection, which prevents the throttle from being retarded in a wind shear condition, namely, a head wind coming at the aircraft that appears to make the air speed go up but in fact causes ground speed to go down. When the separation of ground speed and air speed increases the autothrottle would not retard the throttle to conserve the energy, because the aircraft is entering a wind shear condition.

As discussed in detail above, the autothrottle moves the aircraft power throttles by independent linear actuators, typically located in the throttle quadrant and commonly attached to the throttle power handle at its connection to the throttle cable. According to one aspect of the invention, the actuator operates by rotating a hardened, precision ground, and polished stainless steel shaft that carries an actuation shuttle as components of the throttle control. The actuation shuttle typically carries two sets of three precision ball bearings mounted at a rotation axis angle relative to the shaft axis. The outer races of the bearings roll on the shaft moving the shuttle along the shaft at a rate proportional to the shaft diameter and the bearing axis angle. The shuttle's thrust is proportional the coefficient of friction between the outer race of the spring loaded ball bearings and the shaft. The shuttle moves accurately along the shaft, much like a threaded lead-screw, but without the threads. It slips at a very repeatable thrust force that is proportional to the spring tension in the bearing carrier. This controlled breakaway force assures that the flight crew can maintain backlash-free control of the engine power, even in the event of a catastrophic malfunction of any of the actuator's components and without having to disengage a clutch. Under manual operation, the throttles cause the shuttle to rotate the brushless motor. This intrinsically safe motor requires precise sequencing of the stator winding to rotate, thereby obviating a drive motor runaway.

According to one aspect of the invention, the autothrottle computer monitors the engine internal temperature, the turboprop's torque or EPR/N1 in a turbofan engine, gas generator speed, prop speed, air data, GPS position, GPS velocity, battery voltage, or the like. The autothrottle uses this information to control the thrust and protect the engines from damage. The power lever controls the engine thrust to control speed while maintaining safe speeds and safe temperatures. Haptic feedback can be used to signal when a change is required.

In a take off mode, the throttles are advanced to a predetermined thrust or optionally to a setting based at least in part on alternative limiting factors. The computer monitors the engine power as the throttles are advanced and the command is reduced if the engine starts to surge or exceed the thrust/torque limit due to ram air.

In climb mode, the throttles are maintained at maximum torque/thrust for the maximum allowed time, typically 3-5 minutes and then automatically reduce to a maximum continuous climb or torque schedule (PWC) as a function of altitude. In this mode, the aircraft autopilot's SPEED-ON-ELEVATOR can be engaged, while the autothrottle protects the engine from over temperature or over torque conditions. As the aircraft climbs to higher altitude, the temperature (TIT) will increase and the temperature protection mode will become active to adjust the thrust to limit the temperature at the maximum continuous temperature. The climb thrust is maintained as the aircraft levels off at cruise altitude or until commanded to change value or Mode.

In an airspeed hold mode, the autothrottle controls airspeed to at a commanded value by a manual mode selection change or automatically by a FMS. The autothrottle will maintain the selected airspeed through climb or descent, except as may be limited by maximum torque, temperature, or altitude rate. The autothrottle can be enabled to limit IAS to 250 knots below 10,000 feet, automatically based on GPS location. The airspeed can be set by a FMS airspeed input. This facilitates RTA and RNP operations that require multiple speed changes. The control computer can be configured to automatically set approach speeds based on aircraft gross weight. In addition, commanding missed approach with the TOGA button can automatically set TO/GA thrust while maintaining engine protection.

A protection mode of the autothrottle is constantly monitoring the aircraft performance and engine performance. The engines are monitored and limited to the established safe limits in torque and temperature. The airspeed is controlled at both under-speed and over-speed including VMO/MMO. Additionally, the AOA can be monitored as well. The autopilot is further configured to compensate for bank angle at low airspeeds.

The autothrottle preferably includes an "engine out mode" (Vmca MITIGATION). A loss of an engine (OEI) on a multiengine aircraft can result in hazardous yaw at speeds below Vmca. In one embodiment, yaw rate sensors are monitored to indicate an asymmetrical thrust condition. Generally, one engine will be retarded to correct for an undesired yaw. The autothrottle computer continually monitors multiple engine parameters and will detect a loss of an engine by triggering on: N1 (compressor turbine) nominally below 40%, and oil pressure nominally below 10 psi with auto-feather active.

The computer computes the amount of rudder authority loss due to the reduction of airflow over the rudder. The autothrottle uses the rudder authority loss to execute the necessary reduction in thrust from the remaining engine to prevent hazardous yaw by the relationship

$$\text{Max thrust}*(\text{IAS}/(Vmca+3))\hat{\ }2.$$

As an example with IAS=72 k and Vmca=88+3 k

$$(75/91)\hat{\ }2=63\%\text{ of Max torque}$$

Maximum allowable torque to prevent hazardous yaw=0.63*2230=1400 ft-lbs.

As discussed above, the system a throttle handle with haptic feedback. Haptic feedback can be used to alert the flight crew with OEI and IAS below VMCa, particularly in an engine-out situation, if the thrust of the remaining engine exceeds the Maximum Allowable Thrust equation above. One or more body rate yaw sensors are used to detect the onset of adverse yaw and the controller will then initiate the haptic crew alert to provide an additional margin of safety to compensate for weight or configuration. The haptic vibration is direction sensitive, such that it will increase the force necessary to further advance the throttle in over speed, over-torque, or over-temperature. The haptic vibration can be configured to hinder further advance and deliberately retard the throttles until the exceedance is cleared. Also, the throttles will be hindered from further reduction with an under-speed or AOA warning and deliberately advance to eliminate an impending hazardous condition.

An automatic thrust control may be user enabled in the takeoff mode that is initiated by a loss of an engine, with the airspeed below VMCa+3 knots. The automatic control will retard the operating engine to a thrust/torque defined by the above equation with the yaw sensor input. The computer monitors the yaw input and if the yaw exceeds 5 degrees when in OEI and at or below VMCa+3 IAS, the computer reduces the thrust on the good engine, to mitigate the yaw.

The autothrottle provides automatic speed selection that can be user activated to automatically set an appropriate maneuvering speed for turbulence penetration and/or Vref for approach speeds based on gross weight.

In one embodiment, simultaneous speed selection of the autothrottle and Autopilot speed hold is not permitted. If the autothrottle detects simultaneous attempts to control speed-on-elevator, the autothrottle will disconnect with a visual alert and a headphone audio alert. In a preferred embodiment, the audio alert is at about 1000 Hz.

As discussed above, the autothrottle is configured to adjust for windshear. Windshear Sense functionality is provided by monitoring ground speed (GS) versus airspeed (IAS) and ambient temperature (SAT). When the aircraft is in landing configuration with gear and flaps deployed, a rapid increase of IAS vs GS disconnects the autothrottle to prevent automatic thrust reduction under the control of the autopilot in response to detection of a sudden increase in

IAS resulting from wind shear. The disconnect alerts the flight crew with and audio and/or visual alert.

According to one aspect of the invention hot-starts are prevented. If an engine is started when it is above a certain temperature, there is a risk of engine damage. The autothrottle controller will receive temperature measurements and prevent engine starts in certain conditions. For example, if the temperature exceeds 500° F. the engine will be prevented from starting. Preferably the starter will turn on to blow air through the engine, which cools the engine. As the air is blowing through the engine, the fuel valve remains closed to prevent fuel from entering the engine so it cannot start. Once the temperature of the engine is below the cutoff temperature the fuel valve can open and the engine can be started.

Preferably, the temperature of the combustion is monitored to make sure a maximum temperature is not exceeded. This temperature monitoring can also be used during flight to control and maintain engine temperature. When a maximum temperature is reached, the autothrottle changes to a temperature control mode. For example, at 18,000 feet, power is controlled as a function of temperature so that the temperature is maintained at a setpoint. In one embodiment, the operating setpoint may be 720° F. Torque, temperature, and speed are adjusted to stay at or below the desired setpoint.

In one embodiment, ADSB data of a first plane, called the lead plane, is used by the autopilot to guide the operation of a second plane, called the follow plane. FIG. **7** is a schematic representation of a segment of flightpath from A to B for a first plane **100**. The flightpath of the first plane **100** will be followed and mimiced by a second plane **100**. The autothrottle of the second plane **200** uses the ADSB data output from the first plane **100** to precisely "follow" the first plane and thereby maintain a desired distance, spacing, path, airspeed, and/or operating maneuvers between the first and second planes. The ADSB data used by the autothrottle is the same ADSB data seen by air traffic control and other planes in normal operation. For example, plane **200** can be instructed to follow two miles behind plane **100**. Plane **200** will "follow" each segment **700**-**760** of the flightpath of plane **100** matching speed, altitude, heading, and the like. Because the second plane is "following" the first plane, a desired or predetermined geometry between the planes is maintained and, therefore, a tightening-up of air traffic can be realized.

As shown, there are seven segments between A and B. At each of these segments, plane **100** varied its speed, heading, altitude, or the like. As plane **200** reaches each of these segments, and each location within each segment, plane **200**'s autothrottle, using the ADSB data from plane **100**, mimics plane **100**. In operation, the autothrottle functions as an autopilot using the lead plane **100** to control the follow plane **200**.

The herein-described and other embodiments of the inventive system, with little or relatively little modification, can also be applied to the automated control of aircraft flight control systems and elements other than the engine throttle controls. For example, the arrangement **10** can be connected or coupled, instead of to the throttle lever, to aircraft control surface elements such as the ailerons, trimtab(s), horizontal stabilizer and rudder to auto-adjust the positions of these flight control surfaces as part of or under the control of the aircraft's autopilot system.

Although example embodiments have been shown and described in this specification and figures, it would be appreciated by those skilled in the art that changes may be made to the illustrated and/or described example embodiments without departing from their principles and spirit.

What is claimed is:

1. An autothrottle system for an aircraft, comprising:

a motor configured to impart rotational movement to a shaft extending from the motor, the motor being mounted on a support;

an actuator assembly operatively connected to the shaft and to an attachment end of a throttle lever, the throttle lever having a control end, opposite to the attachment end, to which manual force can be applied;

a position sensor operatively connected between the motor and a moving portion of the actuator assembly; and

an electronic controller configured to control the motor to cause movement of the throttle lever so that the motor moves the actuator assembly along the shaft based at least in part on at least one of position information received from the position sensor and an engine operating parameter monitored by the controller,

wherein when a condition exists such that an actual engine performance differs from a preferred engine performance, the autothrottle advances or retards the throttle lever in a regulated manner for optimal performance of the engine over different regions of engine power output.

2. The autothrottle system of claim **1**, wherein the position sensor is an optical sensor.

3. The autothrottle system of claim **1**, wherein the controller is configured to cause the throttle lever to vibrate, thereby providing haptic feedback to a user under a defined condition.

4. The autothrottle system of claim **1**, wherein the position sensor comprises a linear potentiometer.

5. The autothrottle system of claim **4**, wherein the controller is configured to monitor one or more of air speed, ground speed, and external temperature to determine a windshear condition.

6. The autothrottle system of claim **5**, wherein the controller is configured to disconnect the autothrottle when the windshear condition is detected to prevent automatic thrust reduction.

7. The autothrottle system of claim **1**, wherein the controller is configured to monitor multiple engine parameters to detect a loss of an engine and to compute an amount of rudder authority loss due to a reduction of airflow over a rudder.

8. The autothrottle system of claim **7**, wherein the controller is configured to adjust yaw by varying a necessary reduction in thrust from a remaining engine by a relationship:

$$\text{Max thrust}*(\text{IAS}/(Vmca+3))\hat{}2,$$

where IAS is indicated air speed and Vmca is a minimum controllable air speed with the lost engine.

9. A method for operating an autothrottle system for an aircraft, comprising:

monitoring an engine temperature;

determining if the temperature is above a setpoint; and

when the temperature is above the setpoint:

preventing engine starting;

directing air to the engine to reduce engine temperature; and

when the temperature reduces below the setpoint, allowing the engine to start.

10. The method for operating an autothrottle according to claim **9**, wherein the engine is prevented from starting by stopping fuel flow to the engine.

* * * * *